Optical link design

Optical link design

- When designing an optical link I usually have a BER requirement that needs to be satisfied

- In order to satisfy the BER, I need to consider the following constraints:

  1) Power budget: P_{launch}- Loss (fibre, connectors,…) – Margin >= receiver sensitivity

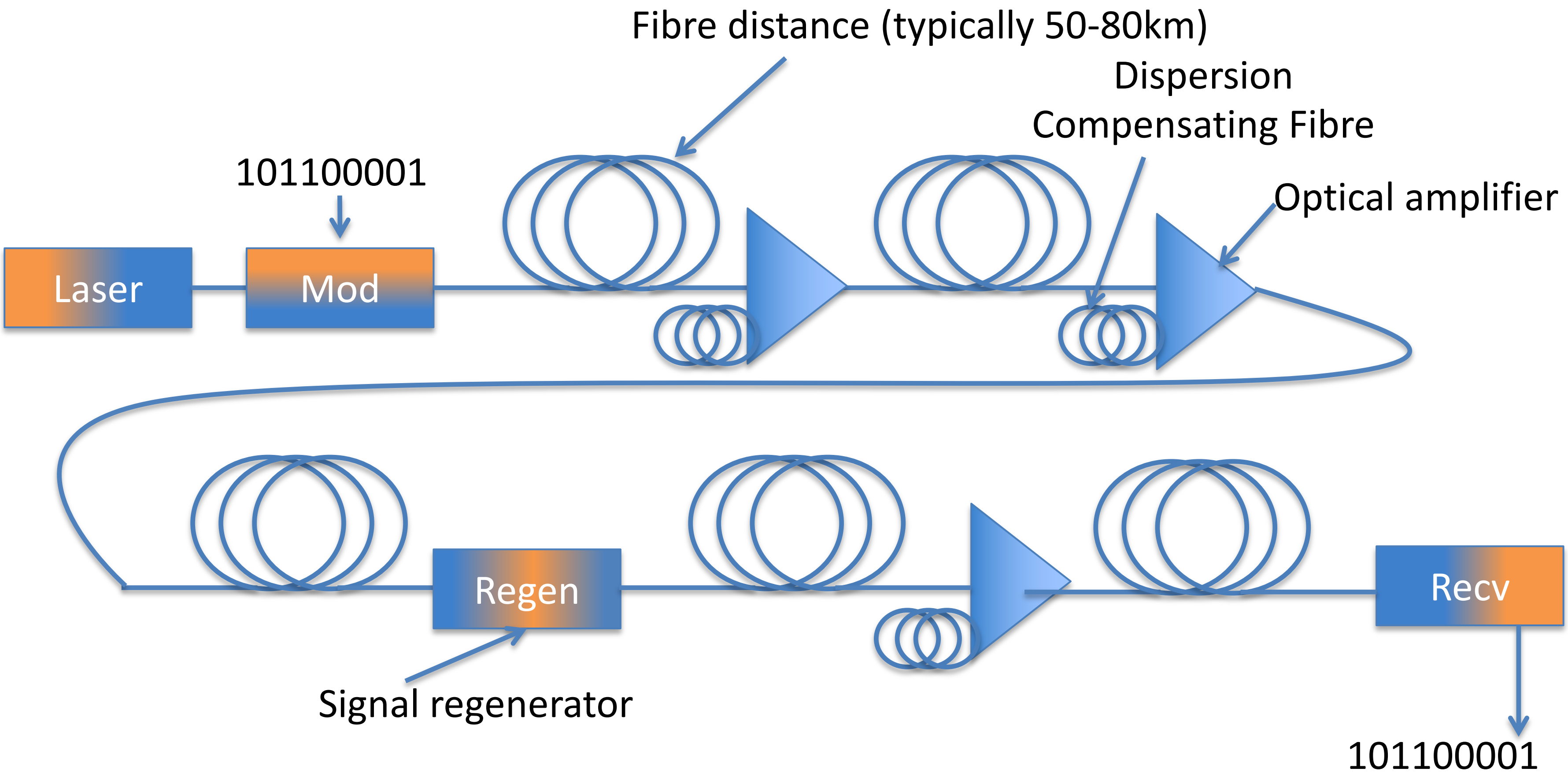
  - power margin=5dB, considers component degradation and other unforeseen events

  2) OSNR: if power budget is satisfied I also need to satisfy OSNR, so that I have a Q-factor good enough to achieve target BER

  3) Other impairments such as dispersion (modal, chromatic and polarization) and nonlinearities need to be accounted for or compensated.

  For 3) we can use the concept of **power penalty ($P_{penalty)}$**: *the increase in the receiver input power needed to eliminate the degradation in the BER caused by fibre impairments (dispersion and nonlinearities)*

Typical optical link



Power budget calculation for amplified systems

- This is the power budget for an amplified system
- The objective is still to make sure that the received power is >= **receiver sensitivity**

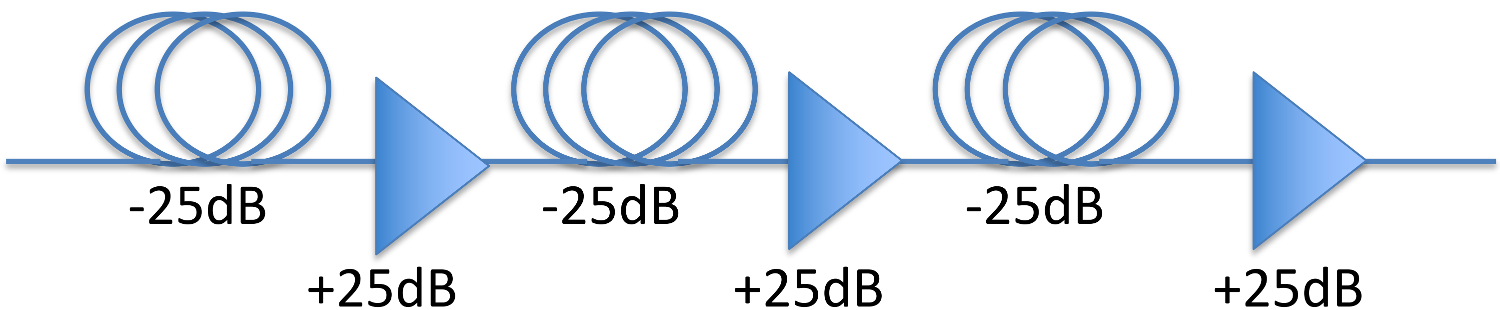
- I sum up amplification gains and subtract losses on a link span and the system margin (M)

$$P_{recv}=P_{launch}-L_1+G_1-L_2+G_2\ldots-L_n+G_n - M > \text{receiver\_sensitivity}$$

- L_i are the losses of each span between two amplifiers. They will include fibre loss, and loss due to additional equipment (e.g., multiplexers, connectors, dispersion compensating fibre, optical switches…)
- Usually spans are all the same length, the amplifier gains G_i tend to be all equal and they should compensate for the loss L_i preceding the amplifier (again, this will include fibre loss, connectors loss, DCF fibre loss, and other components that might be in the span)

Chain of amplifiers

- For long distances, multiple optical amplifiers are used in cascade
- Each amplifier needs to provide enough gain to overcome the loss of its previous span



- High gain in the amplifiers increase the ASE noise. Distance between amplifiers can be reduced to decrease the amount of ASE in the system
- Since each amplifier adds noise, the OSNR deteriorates.
- In long-haul systems, before the OSNR becomes too low, the signal needs to be regenerated.

Noise in optical systems

- In optical systems there are three main types of noise

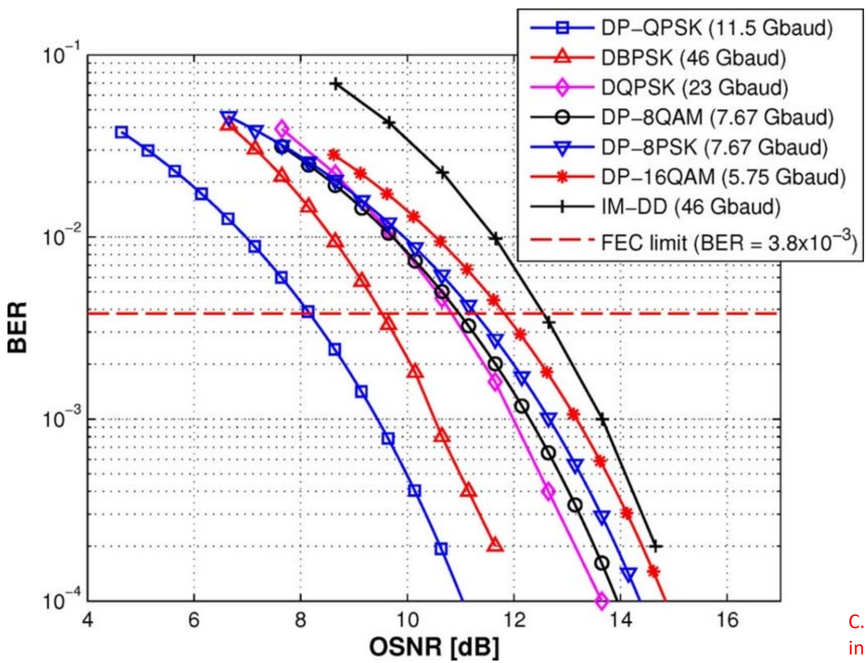
- **Amplified Spontaneous Emission (ASE)**: due to optical amplifiers, which besides amplifying the signal carrying information also introduces additional noise.

- **Thermal noise**: due to the random thermal-driven motion of electrons at the receiver, which sums up to the signal carrying information

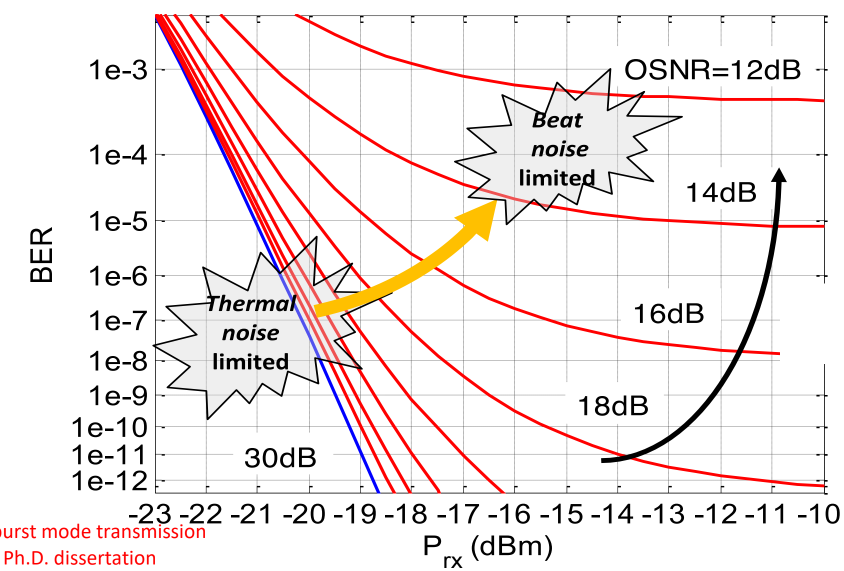
- **Shot noise**: due to the quantistic nature of an optical signal, the photons carrying the information arrive at the detector with random arrival times

BER and OSNR

- The optical signal-to-noise ratio, is the relation between the power of the signal and the power of the noise at the receiver.
- The optical noise is due to the presence of optical amplifiers
- The higher the OSNR value, the easier will be to determine whether a received bit has a 0 or 1 value.
- The curves depend on the modulation format.. The closer are the symbols the higher the probability of error



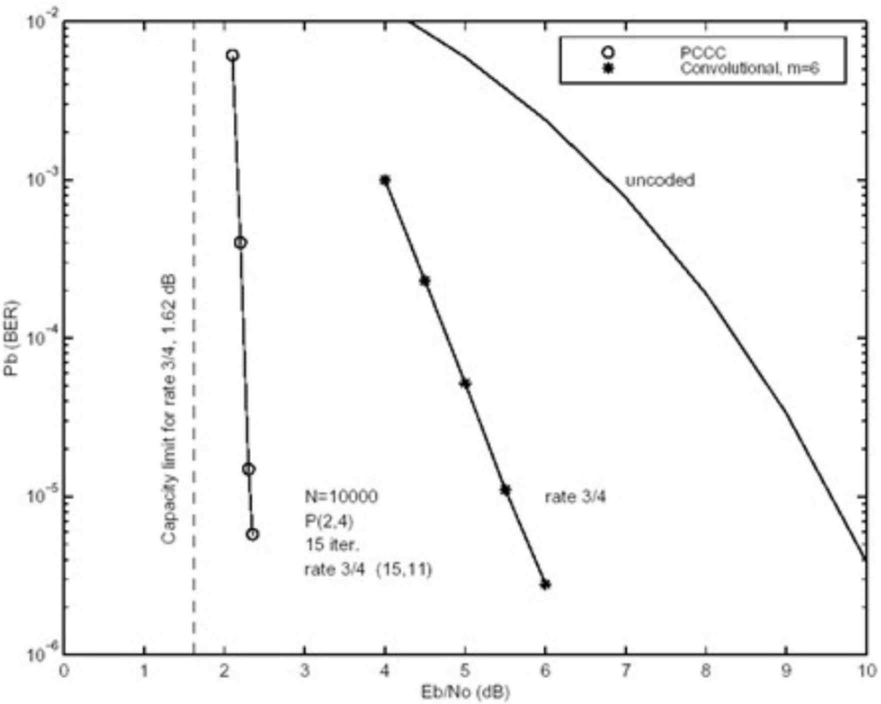
If there are no amplifiers then the optical noise will be low and the limiting factor will be the electrical thermal noise at the receiver



C. Antony. 10Gb/s burst mode transmission in Long Reach PON. Ph.D. dissertation

Error correction

- Error correction codes are widely used in telecommunications.
- Typically turbo codes are used in optical communications, which are very close to the Shannon limit and have a very steep curve.
- The maximum BER that a code can correct is called the Forward Error Correction threshold.



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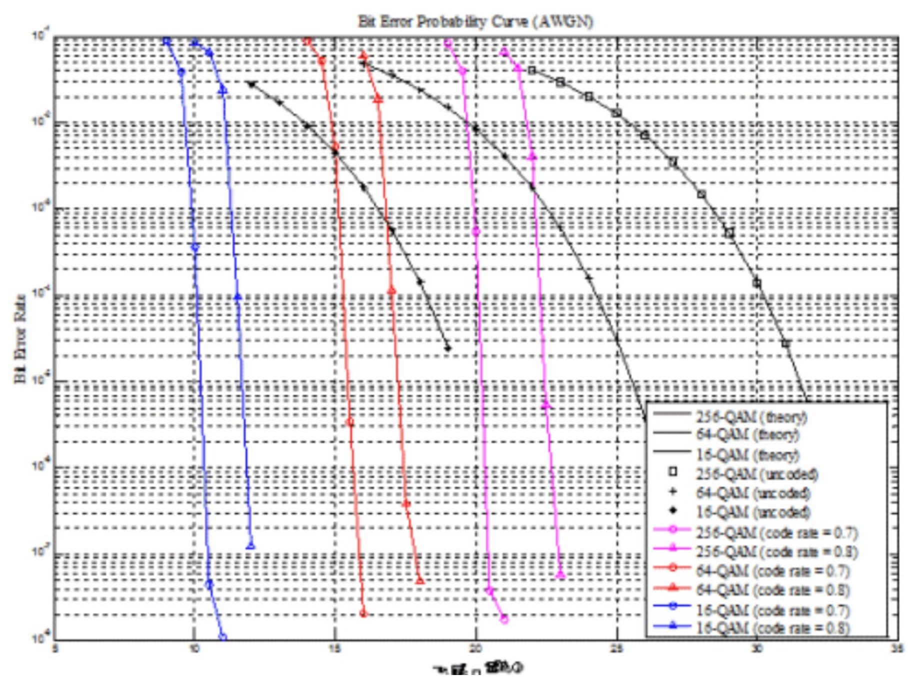
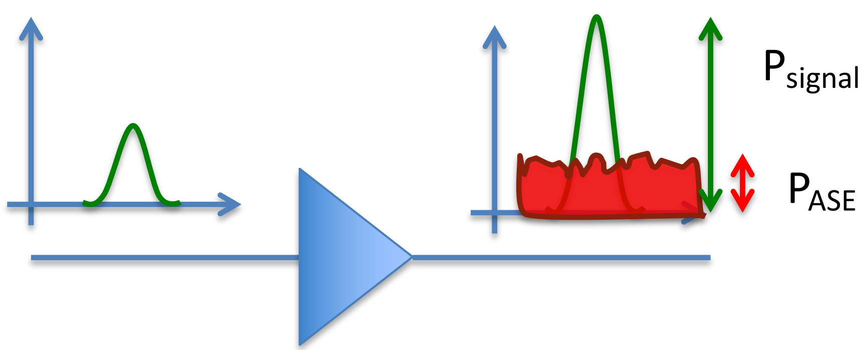


https://www.design-reuse.com/articles/31907/turbo-decoder-architecture-qpp-interleaver-3gpp-lte-lte-a.html

Optical amplifiers and noise

- Optical amplifiers can amplify all incoming optical signals in one fibre.
- However they generate noise, by adding due to This generates a noise called Amplified Spontaneous Emission (ASE)
- Each time the signal is amplified more noise is added

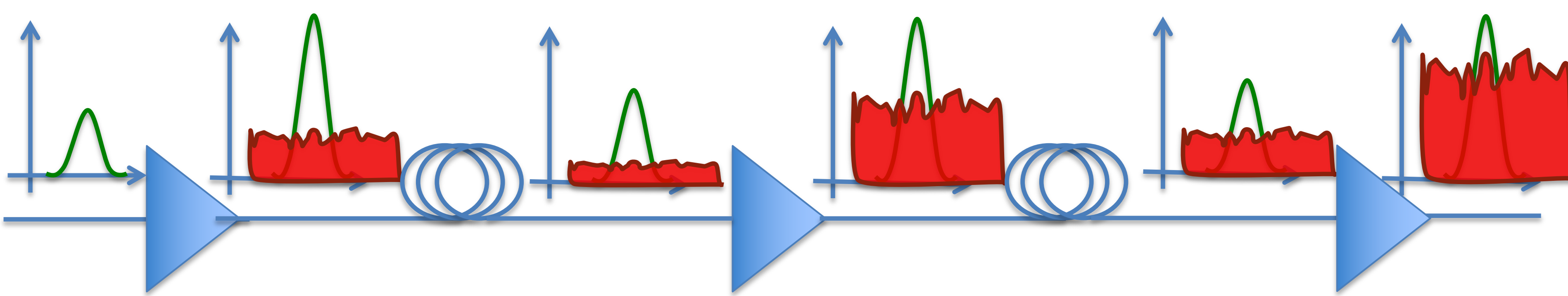
- This phenomenon can be captured by the Optical Signal to Noise Ratio. OSNR=P_{signal}/P_{ASE} (calculated over a reference bandwidth)



OSNR for a chain of amplifiers

- The noise figure (NF) is a measure of the noise introduced in the system by an amplifier
- It's measured in dB and depends on the amplifier type, its gain,...
- An average working value for EDFAs can be NF=5-6dB
- **Typically amplifiers are spaced 80Km apart, but this can change**
- **Reducing their spacing increases the system OSNR**

- In an chain of amplifiers, each additional amplifier amplifies both incoming signal and incoming noise, plus it will add its own noise
- After each amplifier the OSNR decreases and **this is permanent, it cannot be recovered!**



Design OSNR calculation

- For a **chain** of n amplifiers the OSNR is:

$$OSNR_{design} = P_{TOP[dBm]} - NF_{ampl[dB]} - G - 10\log_{10}(N_{Ch}) - 10\log_{10}(n) + 58_{[dB]}$$

- P_{TOP} is the EDFA output power in dBm, NF the noise figure of the EDFA
- G is the amplifier gain, which is typically set to the span loss= $\alpha_{[dB/km]} L_{span[km]}$
- N_{Ch} is the number of channels (i.e., the EDFA output power is shared across N channels)
- You can see form this that reducing the amplifiers spacing increases the OSNR
- n is the number of amplifiers in the link
- 58 is a constant related to the central wavelength of the spectrum
- Notice that the OSNR increases with shorter span lengths

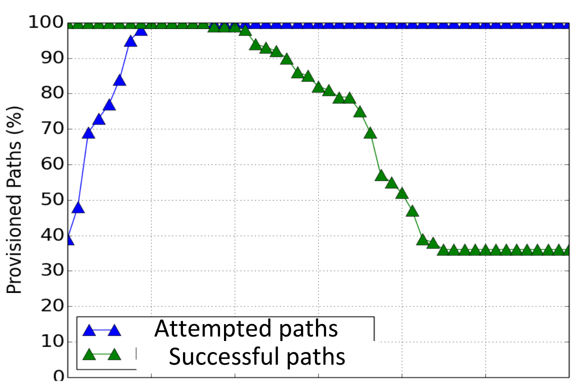
What are margins?

You are close to the cliff edge:
- The closer you get the better (the more efficient you are)
- How safe is it to get closer to the edge, when you can't see it clearly?

Margin = safety distance (signal to noise ratio) you decide to keep, not being sure where you stand with respect to the edge

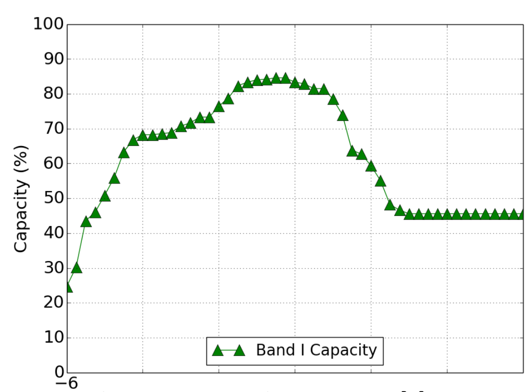
In optical communications the margin is the distance to the FEC (Forward Error Correction) Threshold

Effect of use of different margins



More conservative Margins More aggressive

Network capacity



More conservative Margins More aggressive

10 dB difference makes the difference between a 100G and 400G channel

Application of Margins to OSNR

Average $OSNR_{design} = P_{TOP[dBm]} - NF_{ampl[dB]} - G - N_{Ch} - 10\log_{10}(n) + 58_{[dB]}$

Average $OSNR_{Nominal} = OSNR_{Design} - ROADM_{Penalties}$

Crosstalk and filtering penalties

Average $OSNR_{Commissioning} = OSNR_{Nominal} - Supplier\_Margins$

Variations in fiber loss, amplifier power, etc.

Worst $OSNR_{Commissioning}$ ➔ The worst OSNR across all channels

The Generalised OSNR also includes impairments (noise) due to nonlinear interference (NLI) $\frac{1}{GOSNR} = \frac{1}{OSNR_{ASE}} + \frac{1}{OSNR_{NLI}}$

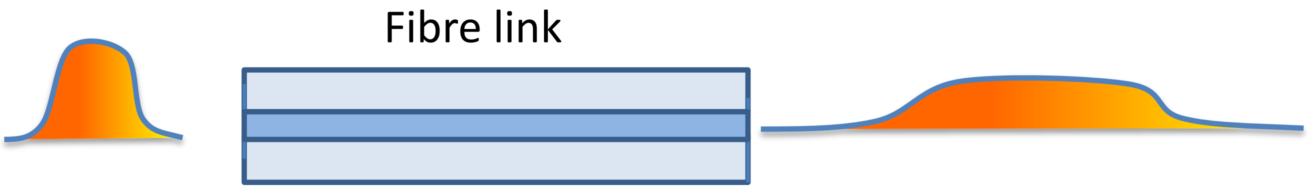
Signal Regeneration

- Before the OSNR drops below the target BER we need to regenerate the signal:
  - you terminate the signal
  - calculate the BER (and make sure it's lower than your target BER)
  - Re-modulate the signal for your next fibre span (like if it was a new signal)
  - For the new span you calculate a new OSNR as you did for the previous span
- **If you regenerate the signal at multiple points the total BER will be the sum of the BER of the individual spans. Remember to take this into account!**
- Regeneration is needed if the OSNR of the total link is too low. If the OSNR is good, but the link budget is low then you might only amplify the signal

Important: *in a WDM system if I decided to put regenerators, I need to put one for every wavelength* ➔ **implies high cost!**

- **For this reason regenerators are only used when absolutely necessary. Often operators sacrifice the signal capacity (i.e., baud rate and modulation rate) to achieve longer distance without regeneration.**

Dispersion



- The spread of the optical pulse in time ΔT is given by:

$$\Delta T = D \cdot L \cdot \Delta\lambda$$

- D is the dispersion coefficient [ps/Km/nm]
- L is the fibre length [Km]
- Δλ is the signal bandwidth [nm]

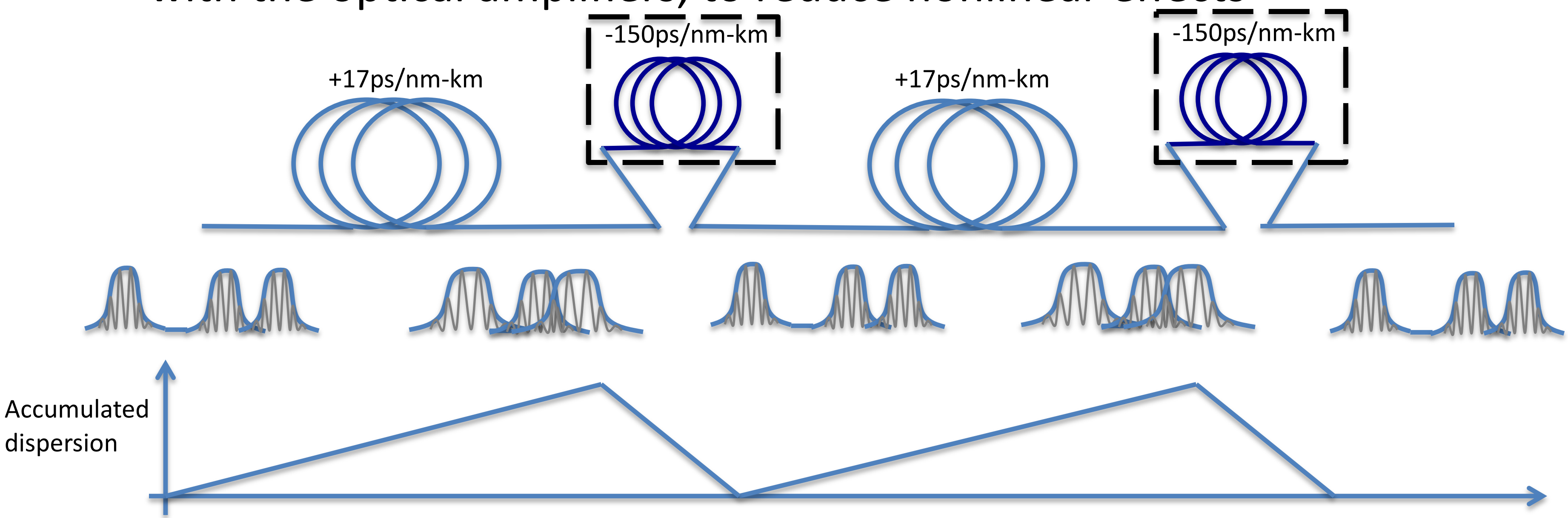
- For each modulation and data rate there's a maximum tolerable dispersion, for which Inter Symbol Interference (ISI) can be tolerated:

$$D \cdot L = \frac{\Delta T}{\Delta\lambda} [ps/nm] < Limit$$

- I have 2 possibilities:
  - If the dispersion is smaller than the dispersion limit, don't do anything and accept the impairment due to dispersion
  - Otherwise, compensate the dispersion to eliminate its effects

Dispersion compensation (used for non-coherent systems)

- If the dispersion accumulated is larger than the limit, it needs to be compensated
- A typical way of compensating chromatic dispersion consists on adding a length of fiber with opposite dispersion characteristic, called Dispersion compensating Fibre (DCF)
- If done with DCF, compensation can be done at the end of the link. However it is usually distributed over multiple stages and co-located with the optical amplifiers, to reduce nonlinear effects



Dispersion compensation

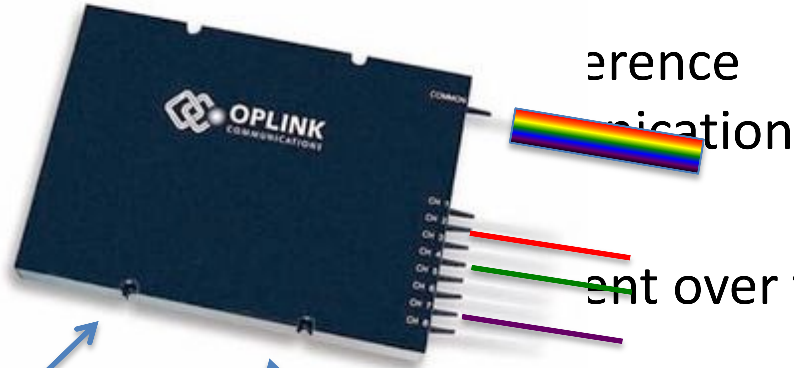
- Dispersion compensating fibre can compensate dispersion on multiple wavelengths at the same time, although the compensation is not perfect along the whole spectrum

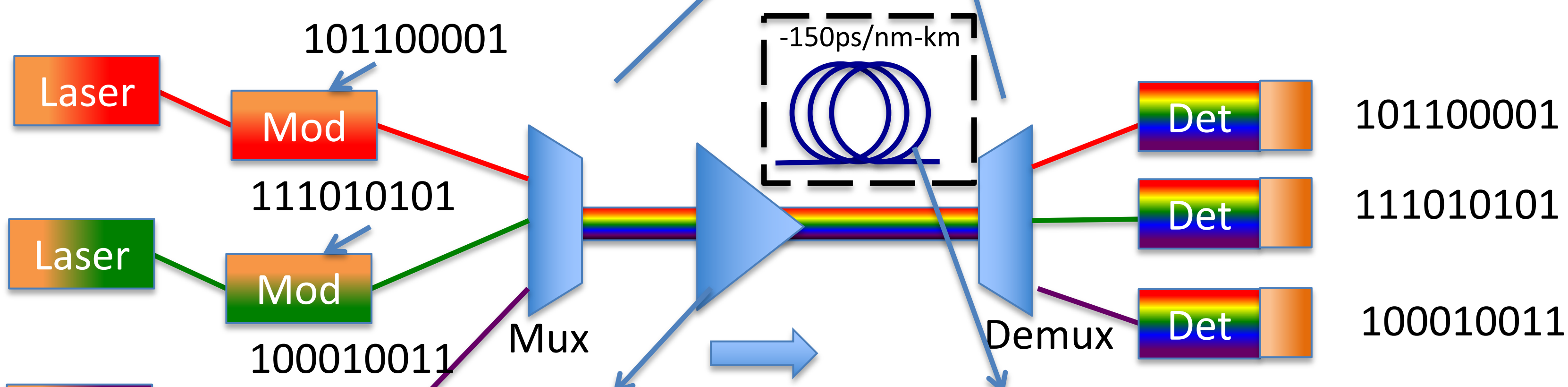
- **Notice that it will introduce a loss, which is usually larger than in standard fibre. This needs to be calculated in the power budget and OSNR calculations!**

- With coherent systems, electronic equalization can be used at the receiver to compensate for dispersion, however
  - The higher the data rate and transmission distance the more processing power and memory is required
  - Coherent receivers are more expensive that direct-detection ones

Wavelength Division Multiplexing (WDM)

- Like in (electric) wired and wir… …erence frequency bands can be used t… …ication channels
- Different wavelengths are indi… …ent over the fiber





The EDFA amplifies all wavelengths, although some are amplified more than others, so the gain is never totally flat over the band

The dispersion is also compensated for all wavelengths, although the compensation is not uniform across the band

WDM

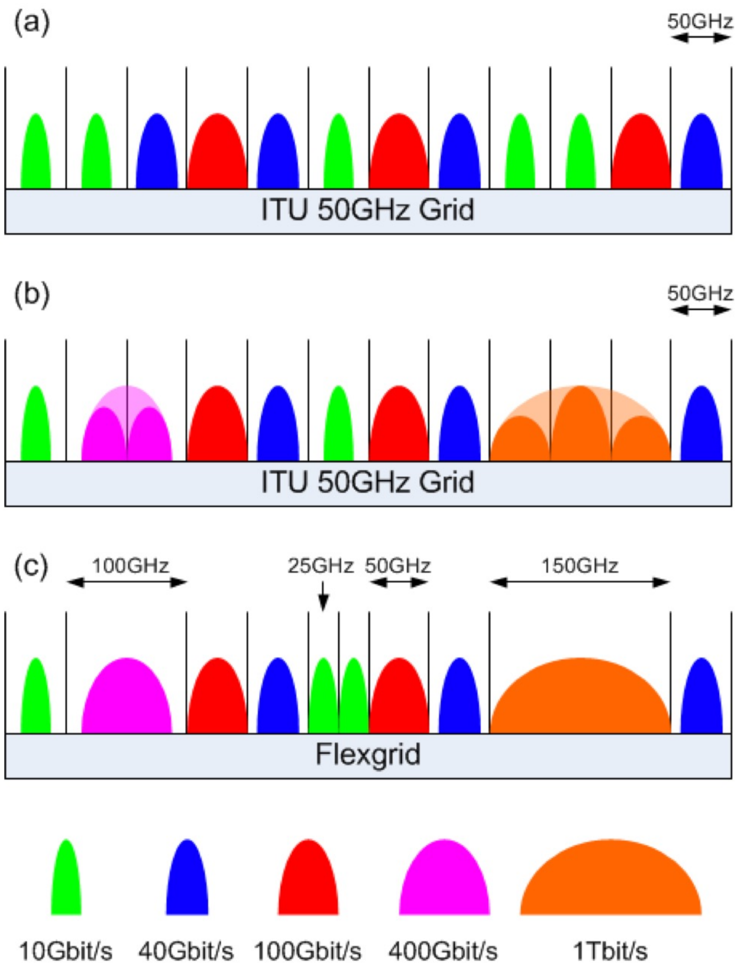
- The ITU-T (International Telecommunications Union – Telecommunication Standardization Sector) has defined a grid for wavelength spacing in the fiber.

- Multiple grids are defined:
- Coarse WDM (CWDM - ITU-T G.694.2):
  - 20 nm spacing: 18 wavelengths in band from 1271 to 1611 nm
    - in C band (1530-1565nm) → 2 wavelengths (1531, 1551)
    - In L band (1565-1625nm) → 3 wavelengths (1571, 1591, 1611)

- Dense WDM (DWDM - ITU-T G.694.1)
  - 100 GHz (~0.8nm): C band - 40 channels
  - 50 GHz (~0.4nm): C band - 80 channels, L band 80 channels
  - 25 GHz, 12.5 GHz not used yet in practical developments

Flex-Grid

- Recently flexgrid systems have been developed. The optical switches can select dynamically slots of different bandwidth (typically a multiple of 6.25 GHz)



Signals need to stay within the 50GHz filter, but this limits the speed to 100Gb/s

If higher rate signals are used, they will occupy higher bandwidth and will be ”notched” by the WDM filters

FlexGrid allows to adapt the filter size, so that higher baud rate signals can be accommodated in the system

P. Wright, et al. “The Network Capacity Benefits of Flexgrid” IEEE ONDM 2013.

A big advantage of a coherent system is that:

A. It’s cheaper to manufacture
B. Does not need a modulator to transmit information
C. Dispersion can be dynamically adjusted for link length
D. The signal can be modulated at higher baud rate